

Feasibility study of Passive Optical Emission Spectroscopy for the electric field measurements in IShTAR

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Abstract. Direct, non-intrusive, measurements of electric fields are essential for understanding the RF-sheath physics. This is especially true in the case of the ICRF antenna - plasma edge interaction in fusion devices. The rectification of the RF-fields near the plasma-facing components of an antenna leads to the development of DC electric fields that accelerate the ions from the plasma towards the antennas' plasma-facing components, enhancing physical sputtering and release of impurities. IShTAR is a device dedicated to the investigation of the plasma - antenna interactions in tokamak edge-like conditions. It has a simplified geometry and enables an easy access and fast modifications, which makes it a suitable environment to develop diagnostics for electric field measurements.

This paper presents the observed Stark effect on He I spectral line profile, with passive optical emission spectroscopy. To be able to fully control the operating parameters, at this initial stage, the measurements are conducted on a simple DC-biased electrode rather than the ICRF antenna. Measured line profiles are compared with the analytical models of the Stark effect in magnetised helium plasma that, as a result of the good fit, provide the electric field strength.

1 Introduction

Auxiliary plasma heating by waves in the ion cyclotron frequency range (ICRF) is an important heating option in magnetic confinement fusion devices. The great advantage is its ability to directly heat the ions in the plasma core in various scenarios with high efficiency. The present-day concern regarding the ICRF heating, however, is its contribution to the heavy-impurity influx originating from the ICRF antenna structure. This has been experimentally observed in various devices that employ ICRF antennas for heating [1–3].

The underlying cause for this spurious phenomenon is not yet fully understood. It is theorised that the formation of the hot spots, erosion and increased physical sputtering from the antenna's plasma-facing components are enhanced by the rectified potential that occurs in the RF sheath established around these areas [4, 5]. Due to this mechanism, also called the RF-sheath rectification, the ions are accelerated out of the plasma with greater velocities than defined by the Bohm sheath criterion, leading to the higher sputtering yields.

To address this issue, and either suppress or completely eliminate these harmful effects, two parallel efforts are ongoing. One approach is to change the design of the

antenna itself [6]. At the same time, an active field of research is the understanding of RF sheath physics for which several theoretical models have been proposed. The development of a numerical description is ongoing. However, the theories are still missing a quantitative experimental verification.

The main goal of our work is to develop a diagnostics method that will provide direct measurements of electric fields in the vicinity of an ICRF antenna, in a simplified geometry compared to the one found in a tokamak, yet in representative environmental plasma-edge conditions. The obtained data will benchmark or even guide the models of the RF sheath physics. The results presented here are the initial spectroscopic measurements of Stark-effect-sensitive helium lines performed on a DC-biased electrode immersed in the helicon plasma source of IShTAR.

2 IShTAR

IShTAR is a test stand dedicated to the RF sheath studies, located at the Max-Planck Institute for Plasma Physics in Garching, Germany. This device is designed to mimic the tokamak edge environment (in terms of plasma density and temperature) especially for studying ICRF antenna - plasma interactions, however in rather simplified

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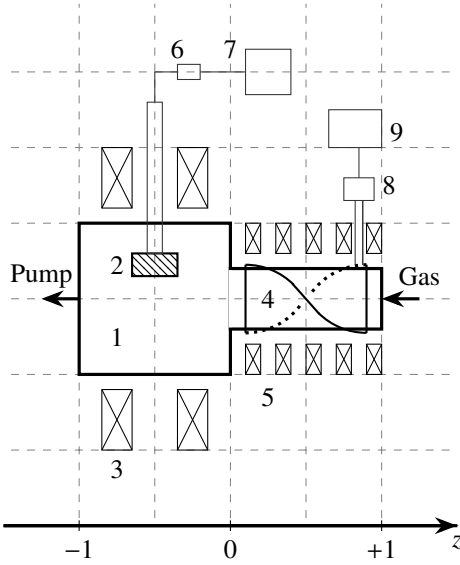


Figure 1: Schematic view of IShTAR: 1 - Main chamber; 2 - single strap ICRF antenna; 3 - Magnetic field coils (Big coils); 4 - Helicon plasma source; 5 - Magnetic field coils (Small coils); 6 - Autotuner; 7 - ICRF generator; 8 - Matching system; 9 - RF generator.

Parameter	Achievable Value
p [mbar]	$10^{-6} - 10^{-2}$
Gas	Ar/He/H
$B_{BigCoils}$ [T]	0.27 (10 s) or 0.4 (pulsed)
$B_{SmallCoils}$ [T]	0.1 (10 s) or 1.0 (coils' limit)
$P_{RFHelicon}$ [MW]	1 (presently 0.003)
$f_{Helicon}$ [MHz]	2-30
ICRF antenna	1 MW (30 MHz), AUG generator 1 kW (5 or 15 MHz), IShTAR gen.

Table 1: Achievable values of the base operational parameters of the IShTAR experiment

geometry required by the numerical models concentrating on this area of research. The design characteristics, choice and range of operational and plasma parameters of IShTAR have been elaborated in [7–9]. The schematics of the machine and its main components is shown in Figure 1. IShTAR consists of a helicon plasma source connected to a larger experimental chamber equipped with an ICRF antenna, referred to as the main chamber. Around both the plasma source and the main chamber magnetic field coils are wound in a Helmholtz-like configuration, providing a parallel magnetic field along the z -axes.

The achievable limits for various parameters are listed in Table 1.

3 Time-averaged passive optical emission spectroscopy

Passive optical spectroscopy is selected as the first approach to directly measure electric fields in the vicinity of

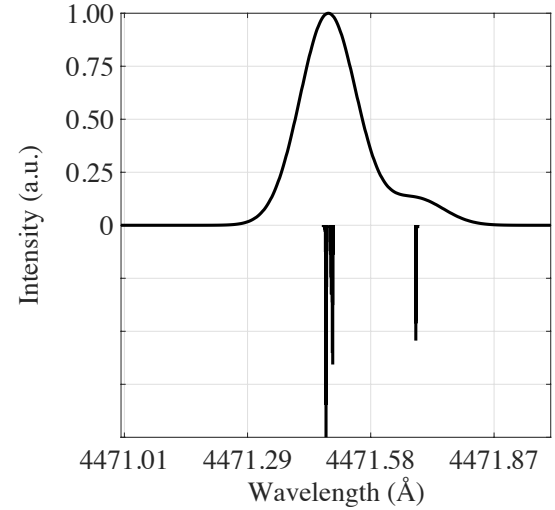


Figure 2: Triplet He-I 4^3D-2^3P line profile simulated with the EZSSS code with no external electric field (reference scenario) shows discrete and continuous results, with the main component at 4471.49 Å and the second component at 4471.6 Å

an ICRF antenna, without disturbing the plasma environment. This technique enables studying the perturbation of the electronic structure of an atom caused by an external electric field, the Stark effect. These perturbations are detectable as a shift of the central wavelength of a spectral line, and the occurrence of forbidden components of the fine structure in a spectral line profile. We have focused our research on the Stark effect on $4^3D - 2^3P$ transitions in helium.

Helium is, beside argon, one of the gases available in IShTAR. However, studying the Stark effect on helium lines is beneficial for two reasons - *i*) the changes on the spectral line profiles caused by an electric field are asymmetrical since both the shift and the forbidden components occur; *ii*) due to the fact that in the so-called orthohelium one electron is always present in the ground state and the energy difference between the ground and the first excited state is large, the wave-functions of the selected transition can be accurately represented by the wave-function of hydrogen, which simplifies the modelling of the spectral lines with the Schrödinger solver. While the sensitivity of an electron in an excited state to an external electric field is increasing with an increasing prime quantum number of the state, n , at the same time the emission intensity is decreasing. For that reason, the $n = 4 - 2^3P$ transition has been selected for this study, since the signal-to-noise ratio of the recorded spectra was acceptable.

Once the time-averaged spectra are recorded, the spectral line profiles are compared to the simulated ones and the electric field amplitude is extracted with the method of least squares. To simulate the spectra perturbed by an electric field, in the presence of a background magnetic field, the Explicit Zeeman Stark Spectral Simulator (EZSSS) [10] was used. This code generates the discrete spectrum by solving the Schrödinger equation in electric

dipole approximation, with external electric and magnetic fields as perturbations. In the second step, by convoluting the discrete spectra with Gaussian and/or Lorentzian profiles to mimic the broadening mechanisms, the continuous spectrum is obtained.

Figure 2 depicts the modelled triplet line profile corresponding to the $4^3D - 2^3P$ He-I transition with no electric field externally imposed on the system. The discrete spectra, calculated with the EZSSS code is shown as a set of lines in the mirror image of the intensity scale. The continuous spectra, presented in the positive part of the Intensity axes is convoluted with a Gaussian distribution corresponding to the Doppler broadening with a temperature of the radiator of 0.7 eV. The distinct feature of these spectra is the occurrence of the second spectral line red-shifted from the main component, corresponding to the fine structure of the triplet transition of helium. This line has intensity of about 10% compared to the main line. Therefore, the experimental data has to be recorded with high signal-to-noise ratio in order to distinguish this component from the noise. Moreover, the spectra have to be recorded with superior spectral resolution to be able to resolve those two components.

4 Experimental setup

To develop a reliable method for measuring the electric fields in the vicinity of an ICRF antenna, the first step is to observe the Stark effect due to a known DC field, in the same plasma that can be found in front of the antenna. Once the concept is confirmed, it will still be used for the calibration of the measurements conducted in the sheath in front of the antenna. Thus a controlled experiment has been constructed that consisted of a planar electrode immersed in the helicon plasma source of IShTAR through the gas-feeding port, as depicted in the Figure 3.

The optical emission spectra was recorded by an Andor™Shamrock750 high resolution spectrometer (focal length 750 mm), equipped with an intensifying CCD detector. The spectrometer is based on a Czerny-Turner optical design and is equipped with 3 gratings of 600, 2400 and 3600 lines/mm. The light from the indicated line of sight was coupled to a 10 m long, 400 μm broadband fibre via an aspherical 6 mm collimating lens with a confocal length of 8.7 nm and an adjustable focal point.

4.1 Operational and acquisition parameters

To detect the expected Stark-effect-induced changes on the spectral line profile, we have used a high-resolution grating with 3600 lines per mm, that provides a spectral resolution of ≈ 0.02 nm.

The discharge parameters for the dedicated set of experiments are listed in Table 2.

Two experimental scenarios have been performed to obtain the results presented here. The reference data were recorded without the voltage applied to the electrode, while the second set was obtained for the set of experiments with the electrode biased to a positive DC-voltage

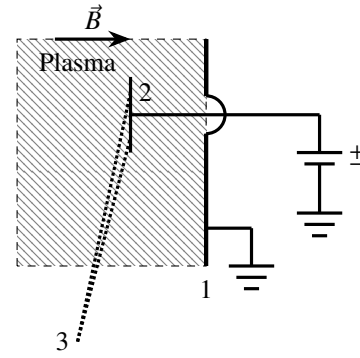


Figure 3: Schematic view of the experimental setup: 1 - Back flange of the plasma source, 2 - Electrode, 3 - Collimating lens and the line of sight indicated in dashed lines.

Parameter	Value
p	7.8×10^{-4} mbar
Gas	He
Gas flow rate	60 sccm
B_{BigCoils}	0 T
$B_{\text{SmallCoils}}$	0.01 T
$P_{\text{RFHelicon}}$	700 W
f_{Helicon}	11.76 MHz
Discharge duration	12 s

Table 2: Discharge parameters for the experiments dedicated to this study

of $U_{el} = 1$ kV, which was the maximum voltage provided by the power supply.

The obtained line profile corresponding to the $4^3D - 2^3P$ transition in He-I were recorded over the whole duration of a discharge, with an exposure time of 0.5 s, in a kinetic series of 24 scans per discharge. The intensifier in front of a CCD sensor of the spectroscopic system provided a relative gain of 8 counts per photoelectron per scan, contributing to the acceptable signal-to-noise ratio. To compare and time-average the recorded data, the scans corresponding to the stable plasma phase were selected, which was an interval of 5 s, thus counting 10 scans per discharge. With the good reproducibility of the line being confirmed, the accumulated spectra were averaged over 4 discharges per scenario (with and without applied voltage on the electrode). This way each of the experimentally recorder line profiles presented here (Figure 4) are the result of 40 averaged spectra.

5 Results and Discussion

The processed data shows a reproducible shift of the He-I $4^3D - 2^3P$ line (Figure 4) when the external electric field is present in the thermal sheath in front of the DC-biased electrode.

For a rough estimate of the electric field expected in a thermal sheath in front of the electrode we can assume that it originates from the difference in potentials between the

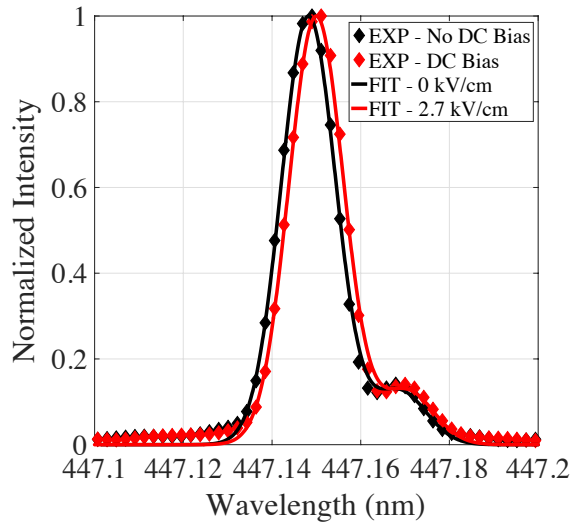


Figure 4: Experimental $4^3D - 2^3P$ He I line profile for $E_{DC} = 0$ kV/cm and $E_{DC} = 2.7$ kV/cm (black and red diamonds, respectively) fitted with the simulated theoretical spectra calculated with the EZSSS code (solid lines)

electrode and the plasma, over the distance corresponding to the sheath thickness. Compared to the potential applied on the electrode, $U_{el} = 1$ kV, the plasma potential is $U_{pl} \approx 0$ kV. The sheath thickness corresponding to the density of helium plasma in ISHTAR of $n_e = 10^{16} \text{ m}^{-3}$, and the electron temperature of $T_e = 5$ eV is proportional to the Debye length of $\lambda_D = 5 \times 10^{-4}$ m. Therefore the electric field in the vicinity of the electrode biased to $U_{el} = 1$ kV, can be estimated to be the applied voltage drop over the sheath thickness - $E \approx 20$ kV/cm. However, the density in this particular plasma volume can not be measured with the diagnostics currently available in ISHTAR, hence the plasma properties listed here could be greatly exaggerated, as are the estimates on the order of magnitude of the sheath thickness since they carry density dependence.

To complete the study, the He-I $4^3D - 2^3P$ transition is simulated with the EZSSS code for several values of the DC electric field, and the best match between the measured and simulated lines corresponds to a simulated spectral line exposed to the external electrical field of $E = 2.7$ kV/cm, as depicted in Figure 4 with the solid lines.

However, it has to be taken into account that in the present setup the emission is collected not only from the sheath region, but from the plasma volume as well. Therefore, the Stark effect induced by the electric fields in the sheath region is shielded.

Even though we were able to detect the electric-field-induced changes on the spectral line profiles, the presently available equipment for these experiments

and the described set-up is not suitable to provide fully trustworthy results. The results presented here are a successful conclusion of proof-of-concept experiments. It is important to note that the further improvements of the set-up are necessary, and ongoing, as it will serve as a routine calibration for the electric field measurements in the vicinity of an ICRF antenna in ISHTAR.

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